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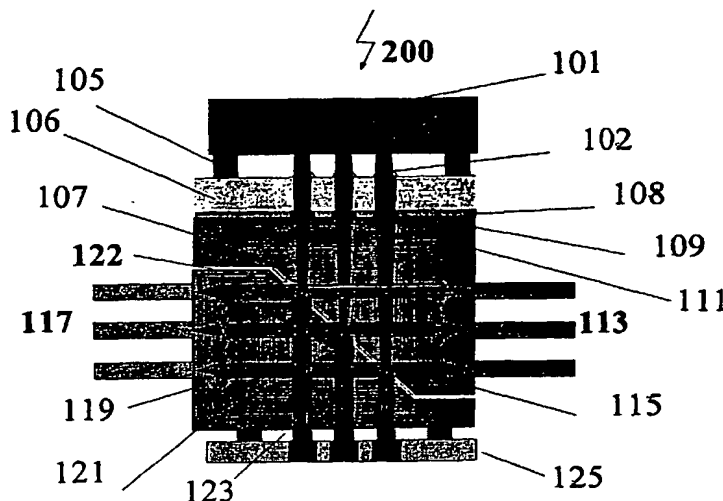
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(54) Title: MULTIPORT OPTICAL AMPLIFIER WITH VCSEL PUMP ARRAY AND GAIN CONTROL



(57) Abstract: An optical amplifier (200) has input means (117) and pump beam generating means (101). Waveguide means (113), such as Erbium-doped fibres, receive the input signal and output amplified signals. The amplifier (200) may have more than 64 input/output ports, and the pump generating means (101) may comprise an array of vertical cavity surface emitting lasers. Gain may be controlled by monitoring input signal and pump powers, and adjusting the pump driving current profile accordingly.

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MULTI-PORT OPTICAL AMPLIFIER WITH VCSEL PUMP ARRAY AND GAIN CONTROL**Field of the Invention**

The present invention relates to an optical amplifier, and, in particular a multi-port optical amplifier using Vertical Cavity Surface Emitting Laser (VCSEL) arrays and
5 other components to provide dynamic pumping. The invention has particular, although not exclusive, utility in optical telecommunications networks, photonic systems, photonic signal processors, and dense optical computer networks.

Background Art

The proceeding discussion of the background art is intended to facilitate an
10 understanding of the present invention only. It should be appreciated that the discussion is not an acknowledgement or admission that any of the material referred to was part of the common general knowledge in Australia as at the priority date of the application.

Along the path of an optical communication system, optical signals are attenuated
15 by optical fibers and other optical components encountered by those optical signal. Optical amplifiers are key devices within wide-area networks, local-area networks, cable TV distribution, computer interconnections, and anticipated new fibre-to-the-home applications, because their signal amplification is independent of the transmission bit rate and data format.

20 Semiconductor optical amplifiers (SOA's) have the advantage of small size. However, they have several disadvantages, including limited gain and bandwidth, low saturation output power, high noise figure, high nonlinearity, and polarization dependent performance. On the other hand, rare-earth-doped fibre amplifiers, such as erbium doped fibre amplifier (EDFA), can provide gain in excess of 40 dB
25 and low noise figure performance. Their features include very low polarization sensitivity, high output power (as high as +37 dBm) and wide-bandwidth (up to 80 nm).

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A rare-earth doped fibre amplifier operates by the same fundamentals as a laser, which is light amplification by stimulated emission of radiation. The fibre amplifier is driven by another optical source (pump) to excite the active dopant (a rare-earth element) in one of its absorption bands. The electrons in the rare-earth ions are pumped to an excited metastable state. The success of rare-earth-doped fibre amplifiers is mainly due to the long emission lifetime of the metastable state, which permits large population inversions - as almost all ions are in a metastable excited state instead of in the ground state - needed to achieve high gain. Rare-earth doped fibre amplifiers can be used for both the 1.3 μm and 1.55 μm optical telecommunication windows. For example, fluoride fibre, doped with the rare earth element praseodymium, is capable of signal amplification at 1.3 μm , whereas, a silica-based fibre, doped with the rare earth element erbium, is capable of signal amplification at 1.55 μm . Existing silica-based EDFA's require long lengths of few metres for efficient gain performance. High concentration erbium-doped phosphate glasses have recently emerged, which can miniaturize the optical amplifiers to such an extent that planar waveguide technology is possible. With the new glass composition, a waveguide of a few centimeters can achieve signal amplification of the same order of magnitude as current amplifiers with a length of about 10 metres.

Future dynamic optical networks will comprise many nodes linked by a number of different fibre optic links for the transport of optical signals there between. In a dynamic optical network, where each signal might be routed through a different group of optical components, a different amount of attenuation is experienced by each signal component. In order to overcome this problem there is a need for a means to cost-effectively and independently amplify optical signals arriving at a node in the multi-port network. Existing EDFA's do not satisfy the market's requirements of low cost, high-performance, efficient power management, and standards. Discrete fibre amplifiers can operate at high bit rates, but they are large and expensive, hence their effectiveness is limited. For example, erbium-doped fibre amplifiers currently enable tens of millions of simultaneous telephone conversations across continents and under oceans on a single fibre-optic cable. But their high cost makes them economical only for long-haul systems, and their large size means that they cannot be integrated easily with other devices. A

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dramatic cost reduction in multi-port, high performance optical amplifiers will make a large impact on the design approach and implementation of future metropolitan and access optical networks.

Disclosure of the Invention

- 5 According to the present invention, there is provided an amplifier of input optical signals, the amplifier comprising:

input means for receiving input optical signals;

beam generating means for generating pump beams; and

- 10 waveguide means for receiving the optical signals from the input means, and pump beams from the beam generating means, the waveguide means being arranged to absorb the received pump beams and operable to amplify the received optical signal using stimulated emission of radiation, the pump beams being used to drive the waveguide means to provide the stimulated emission;

- 15 wherein the beam generating means is a vertical cavity surface emitting laser.

- Preferably, the amplifier further comprises routing means for receiving the input optical signals from the input means, and pump beams from the beam generating means, and for routing the received input optical signals and the pump beams to
20 the waveguide means.

Preferably, the routing means comprises a glass or sapphire substrate.

Preferably, the routing means includes collimating and focusing means. Preferably, the collimating and focusing means comprise a microlens array, or, alternatively, diffractive optical elements.

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Preferably, the amplifier further comprises monitoring means for monitoring the power of the optical signals and the pump beams. Preferably, the monitoring means is a two-dimensional photodetector array.

Preferably, the vertical cavity surface emitting laser is an integrated circuit,
5 integrated with the photodetector array.

Preferably, the input means has a multi-port configuration, particularly an array of optical fibres.

Preferably, the waveguide means has a multi-port configuration comprising an array of optical fibres.

10 Preferably, the fibres in the fibre array are either core-pumped or cladding-pumped.

Preferably, the array comprises erbium-doped alumino-silicate fibres, or praseodymium-doped fluoride fibres.

Preferably, the vertical cavity surface emitting laser operates in transverse single-
15 mode. Alternatively, the vertical cavity surface emitting laser operates in multi-mode.

Preferably, the vertical cavity surface emitting laser is arranged with an external cavity resonator.

Preferably, the amplifier further includes a first detecting means for detecting
20 pump beam signals, and a processor to which pump beam monitoring signals are supplied, from the first detecting means, in response to the detected pump signals, the processor being operable to generate control signals for controlling the pump beam generating means, in response to the pump beam monitoring signals.

25 Preferably, the first detecting means is a photodetector array integrated on a semiconductor chip.

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Preferably, the amplifier further includes a second detecting means for detecting the input signal beams, with input monitoring signals being supplied from the second detecting means to the processor in response to detected input signals, the processor being operable to generate control signals for controlling the beam
5 generating means, in response to received input monitoring signals, and pump beam monitoring signals.

Preferably, the second detecting means is a photodetector array.

In a preferred embodiment, the optical amplifier comprises:

- 10 an optical substrate having top and bottom faces and two side faces extending between the top and bottom faces so that the substrate has a square-shaped cross-section;
- an input fibre array and an output doped fibre array respectively coupled to the side faces in alignment with each other, the input fibre array supplying input beams;
- 15 a vertical cavity surface emitting laser (VCSEL) array and a top photodetector array arranged in series proximate to the top face, the VCSEL array generating pump beams;
- a bottom photodetector arranged proximate to the bottom face in alignment with the VCSEL array and the top photodetector array;
- 20 a routing element arranged in the substrate at 45° to the side faces having a beam splitting lower surface and a reflective upper surface, the lower surface transmitting a major portion of the input beams to the output doped fibre array and reflecting a minor portion of the input beams to the bottom photodetector array, the upper surface reflecting the pump beams to the
25 output doped fibre array; and

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a processor for adjusting the power level of the pump beams in response to the power levels detected by the top and bottom photodetector arrays so that the gain of the optical amplifier can be selectively controlled.

5 This preferred embodiment eliminates free space beam propagation and allows the optical amplifier to be more compact.

Preferably, the optical amplifier further includes an input microlens array etched in the optical substrate for collimating the input beams.

10 Preferably, the optical amplifier further includes an output microlens array etched in the optical substrate for coupling the input beams and pump beams to the output doped fibre array.

Preferably, the bottom photodetector array is flip-chip bonded to the optical substrate.

Preferably, the VCSEL array is flip-chip bonded with an Ultra-Thin Semiconductor (UTS) chip that integrates the top photodetector array.

15 Preferably, the output doped fibre array is an erbium doped fibre array.

Preferably, the optical substrate comprises a glass or sapphire substrate.

In accordance with another aspect of the present invention, there is provided a method for controlling the optical gains of an optical amplifier, the amplifier comprising at least one optical fibre amplifier and a pump source, the method
20 comprising the steps of:

measuring the power of pump beams generated by the pump source and deriving a first signal representative thereof;

measuring the power of input optical signals and deriving a second signal representative thereof;

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estimating the signal gain based on the measured input signal power and pump power, and deriving a third signal representative of the difference between the measured signal gain and the desired signal gain;

5 processing the first, second, and third signals to generate a pump source driving current profile in response to the processed first, second and third signals; and

controlling the generation of driving current profile to achieve the desired output power for the pump beam.

10 This has the advantage of providing an integrated, high-power multi-port optical amplifier structure that uniquely integrates independently controlled pump sources, drive and operational componentry to provide variable optical gain to dynamically compensate for the optical losses in multi-port fibre-optic systems. Preferred embodiments of the invention have a reduced complexity and draw less power than most modern systems.

15 Brief Description of the Drawings

The invention, will now be described, by way of example only, with reference to the accompanying drawings, of which:

Figures 1A and 1B schematically illustrates the concept of rare-earth-doped fibre amplification;

20 Figure 2 schematically illustrates a multi-port optical amplifier;

Figure 3 schematically illustrates pumping an EDFA using a VCSEL source in accordance with the present invention;

Figure 4 illustrates a two-dimensional (2D) optical amplifier architecture for an amplifier of the present invention; and

Figure 5 illustrates a schematic of a second embodiment of a 2D optical amplifier architecture in which a single 45° edge is used to route the signal and pump beams.

Best Mode(s) for Carrying Out the Invention

- 5 Figures 1A and 1B illustrate the principle of optical amplification in an erbium-doped optical fibre amplifier (EDFA) 1. Figure 1A is a schematic representation of an EDFA, and Figure 1B is an energy level diagram for the EDFA of Figure 1A.

The basic energy diagram of an EDFA is very similar to a 3-level laser system. Supplying photons in a pump wavelength, λ_p (usually 980nm), excites the erbium
10 electrons (i.e. increases their energy) to the excitation level. Then the excited electrons undergo a non-emission transition – that is a slight loss of energy - to a metastable level that has a long emission lifetime of approximately 10 ms. Light photons in a signal wavelength, λ_s (usually about 1550nm), are amplified by
15 stimulated emissions, and as in a laser, the emitted photons then stimulate other emissions, leading to an exponential growth of signal photons. The long metastable emission lifetime allows high quantum efficiency and low noise figure to be attained. If the metastable emission lifetime were short, then electrons are relaxed too quickly, meaning more photons are spontaneously emitted giving rise to spontaneous noise, and more input pump is needed to keep the electrons in
20 the metastable state.

The EDFA 1 requires a 880nm pump laser 2, a coupler 3, which combines a laser beam from the pump laser 2 with an input signal laser beam 4 into a single fibre 5, and the EDFA 1, which is the amplification medium. Sometimes, an optical filter (not shown) is used, after the EFDA 1, to filter out the amplified spontaneous
25 noise.

There are several wavelengths that optical fibres can carry. Erbium ions (Er^{3+}) have quantum levels that allow them to be stimulated to emit in the 1550nm band, which is the wavelength of minimum power loss in most silica-based fibres. That gives them the ability to amplify signals in a wavelength where high-quality

amplifiers are most needed. EDFA's can be excited by a signal at either 800nm or 980nm, both of which silica-based fiber can carry without great losses, but aren't in the middle of the signal wavelengths. Those wavelengths are also far enough away from the signal wavelength of 1550 nm thus allowing the pump beam and the signal beam 4 to be easily separated. Erbium can also be excited by photons at 1480nm, but this is typically undesirable because both the energy pumping process and the stimulated emission by the signal take place in the same energy band, which causes interactions that lower the efficiency of the EDFA and increase the amplifier noise.

Another important property of erbium for use in an EDFA is that it is fairly soluble in silica, making it easy to dope into mixtures for making silica-based fibres, and by using a co-dopant, such as Al_2O_3 , $\text{GeO}_2\text{-Al}_2\text{O}_3$, or P_2O_5 , the erbium compound's solubility in the silica mixture can be greatly increased, and some of the EDFA's properties can be improved. For example, $\text{GeO}_2\text{-Al}_2\text{O}_3$ can be used to almost double the time it takes for excited erbium to relax, which therefore almost doubles the quantum efficiency of the EDFA.

One disadvantage of EDFA's is that their gain varies with a signal's wavelength, which creates problems in many wavelength division multiplexing (WDM) applications. This can be solved by using special optical passive filters that are designed to compensate for the gain variation of the EDFA.

Figure 2 illustrates the basic principle of an optical amplifier 100 of the present invention. In this description, a plurality of inputs and outputs are described – that is a multi-port amplifier is described. However, it should be noted that this invention applies to single or multiple input and/or single or multiple output systems.

A multi-port optical amplifier 100 comprises an input fibre array 10 for carrying input signal beams, coupled to an input fibre collimator array 11, which converts the input signal beams into collimated beams 12. A VCSEL array 14 generates an array of pump beams 15 perpendicular to the signal beam direction. The pump beams 15 and the collimated signal beams 12 are combined using a WDM

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beam combiner 13. The combined beams 16 output from the combiner 13 are then coupled into an output array 18 of rare-earth doped fibres via a fibre focuser array 17. The gain of each output port of the fibre array 18 is controlled by the amount of VCSEL pump beam 15 coupled into that particular port. The amount of
5 pump power coupled into an output port can be adjusted by adjusting the current that drives the relevant portion of the VCSEL array 14 associated with that particular output port.

It should also be noted that in free-space multi-port optical processors (e.g. optical switches) the optical signals are inherently converted to free-space beams for
10 parallel processing. After processing, the optical beams undergo different attenuations - which necessitate post optical amplification and equalization. It can be seen from Figure 2 that combiner 13, the VCSEL array 14, and the fibre array 18 can be integrated with a free-space multi-port optical processor to combine the pump beams 15 and the signal beams 12, yielding multi-port amplification as well
15 as gain control (by controlling the power of the VCSEL).

Having described the basic principle of the optical amplifier of the present invention, the concept of pumping an EDFA, using a VCSEL as the pump source will now be discussed, with reference to Figure 3.

As can be seen in Figure 3, a VCSEL 20 is used as a pump. The VCSEL 20
20 generates a diverging optical beam 21. In practice, the divergence angle is less than 5°. A VCSEL microlens 22 is integrated with the VCSEL 20 to collimate the VCSEL beam 21. The VCSEL 20 is flip-chip bonded with an Ultra-Thin Semiconductor (UTS) chip 24 that integrates a photodetector monitor 23 to monitor the power of the pump beam from the VCSEL 20. The UTS chip 24 is
25 bonded to a glass substrate 25 whose one edge 29 is cleaved at 45° with respect to the direction of the VCSEL beam 21. This edge 29 allows the VCSEL beam 21 to undergo total internal reflection after being incident on the edge 29. The edge 29 is externally coated with an anti-reflecting coating. The wavelength of the anti-reflecting coating is selected so that a free-space input signal beam 26 incident at
30 the edge 29 from a horizontal direction – that is perpendicular to the VCSEL beam 21 – will pass through into the glass substrate 25 and combine with the VCSEL

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beam 21. A microlens 27 is etched directly into the glass substrate 25, and its focal length and position optimized, so that the VCSEL beam 21 and an input signal beam 26 into the core of the EDFA 28, wherein the pump beam is absorbed, and the signal beam is amplified.

- 5 The VCSEL beam 21 emitting from the VCSEL 20 is efficiently coupled to the doped optical fibre 28. The coupling efficiency of the VCSEL 20 to the EDFA 28 is maximized by optimising the position and the focal length of the integrated VCSEL microlens 22. The coupling efficiency of the input signal beam 26 to the EDFA 28 is maximized by optimising position and focal length of the integrated
10 glass microlens 27.

Several lens manufacturers (e.g. Edmund Scientific, Newport) now offer anti-reflection coating with substantially reduced reflection loss for various wavelengths in optical telecommunications. The EDFA gain is proportional to the amount of pump beam power coupled into the EDFA 24. It is therefore possible
15 to adjust the amount of VCSEL beam 21 coupled into the EDFA 28 so that arbitrary gain is achieved by controlling the amount of pump beam coupled into the EDFA 28. To achieve maximum pumping efficiency, the lengths of the doped fibers are optimized to provide the maximum possible small-signal gain at the maximum available VCSEL pump power. A single VCSEL 20 and EDFA 28 have
20 been described above with respect to Figure 3. However, in a preferred embodiment of the present invention, a VCSEL array and an EDFA array can be used.

Currently, 980nm VCSEL arrays can generate more than 100 mW of optical power per VCSEL element. For a 64-port doped EDFA fibre array, and 70%
25 pump coupling efficiency, 70 mW of pump power can be coupled into each output port – that is port of the EDFA array. If the length of the doped fibre in the array is optimized and the optical signal power is small (< -10 dBm), more than 13 dBm of output optical signal power can be obtained over the optical telecommunications C band (1530 – 1560 nm). Note that commercially available gain-flattened and
30 gain-clamped EDFA's can be used in the present invention.

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As mentioned above, VCSEL and EFDA arrays can be used. Figure 4 illustrates an embodiment of an optical amplifier 100 of the invention using such arrays.

The optical amplifier 100" comprises a 2D input fibre array 30 with a 2D input microlens array 31 etched directly into a glass substrate 32 in order to collimate
5 input signal beams 34 from the input fibre array 30. The glass substrate 32 has a V-groove shape 41 with a left edge 33 is cleaved at 45° and coated with an anti-reflective coating to pass a large proportion of the input signal beams 34 through into the glass substrate 32, while reflecting a low-power monitoring signal beam 35 to a flip chip photodetector array 40, for monitoring the input signal beam – as
10 will be discussed in more detail below. The photodetector array 40 is bonded to a UTS chip 60 that integrates a pump photodetector array (not shown) for pump beam power monitoring, and is attached to the glass substrate 32. The right edge 36 of the V-groove 41 is also cleaved at 45°, and perpendicular to the left edge 33. The right edge 36 is also coated with an anti-reflective coating to pass the
15 signal beams 34 through with minimum reflection. The V-groove 41 can be free-space or any index matching glass.

In an alternative, the glass substrate 32 can be replaced by a sapphire substrate. Sapphire has attractive properties that make it a competent material that can be grown to arbitrary shape: including lens etching with close dimensional tolerances
20 and special surface finishes.

At the output of the glass substrate 32, there is provided a microlens array 37. The microlens array 37 is used focus the signal beams 34 and couple them into the output ports of an EDFA array 38, and is also directly etched onto the glass substrate 32. In an alternative embodiment, the microlens arrays 31, 37 can be
25 replaced by diffractive optical element relays. The EFDA array 38 comprises rare-earth doped fibre collimator waveguides – either erbium-doped alumino-silicate or praseodymium-doped flouride. The fibres can be either core-pumped or cladding-pumped.

A 2D VCSEL array 50 is used to supply the pump beams 39 for input to various
30 ports of the EFDA array 38. The pitch of the VCSEL array 50, the input microlens

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array 31, the photodetector array, the output microlens array 37, the input fibre array 30, and the EDFA array 38 must be equal.

The VCSEL array 50 can operate in a transverse single mode, where the EDFA array fibres are core pumped. In an alternative embodiment, the VCSEL array 50
5 can operate in multi-mode for cladding-pumped EDFA array fibres.

In an alternative embodiment, an external cavity resonator (not shown) can be used in conjunction with the VCSEL array 50 to provide higher effective active diameter and improved loss discrimination between transverse modes.

The detected signal beam and pump beam powers are supplied from the
10 respective photodetector arrays to an electronic processor 46, via a detected signal power bus 42 and a detected pump power bus 44. The processor 46 is operable to estimate the required pump powers - for desired EDFA gains - and to generate the driving currents 48 for the various VCSEL elements of the VCSEL array 50. When the VCSEL array 50 is operated in the active region, the
15 relationship between the output pump power and input driving current is linear. This means that the estimation of the required VCSEL driving current requires one multiplication operation and one addition operation. When the signal power is small, the EDFA gain can be calculated from the pump power via a simple expression. However, in large-signal regimes, the EDFA gain depends non-
20 linearly on the input signal power as well as the pump beam power. This requires a complex iterative algorithm and a storage medium to accurately estimate the required VCSEL driving current for an EDFA gain target.

In particular, the method for controlling the gains comprises the steps of measuring the power of pump beams generated by the VCSEL array 50 using the
25 photodetector array integrated in the UTS chip 60, and deriving a first signal representative thereof, measuring the power of input optical signals using the photodetector array 40, and deriving a second signal representative thereof. The processor 46 is then operable to estimate the signal gain, based on the measured input signal power and pump power, and to derive a third signal representative of
30 the difference between the measured signal gain and the desired gain. Thus,

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when there is a difference between the measured signal gain and the desired gain, this value of this representative third signal becomes nonzero, and enables a VCSEL current increment needed to maintain the desired signal gain to be calculated. That is, if the input signal power changes by ΔS , then third signal
5 representative will be the difference between the desired gain and the measured gain, i.e. $\Delta G = G_{\text{desired}} - G_{\text{measured}}$. The algorithm uses the third signal representative to calculate the corresponding VCSEL current increment, ΔI , necessary to retune the gain to the desired value.

So, the processor 40 is operable to process the first, second and third signals,
10 and to generate a VCSEL array 50 driving current profile in response to the processed first, second and third signals; and, further, to control the generation of driving current profile to achieve the desired output power for the pump beam.

An alternative embodiment, shown in Figure 5, utilises the same concept used in Figures 4, except that the signal monitoring photodetector array 125 is flip-chip
15 bonded to the optical substrate so that it is opposite parallel to the VCSEL array 101. This eliminates free-space beam propagation and allows the device to be more practical. The in-fibre optical signals are collimated by a microlens array 119, etched directly into the optical substrate. Small portions (< 5%) of the collimated signal beams 121 are reflected by the 45° coated edge 122 and
20 photodetected by the flip-chip bonded signal-monitoring photodetector array 125. The high portions of the signal beams are coupled to the output erbium-doped fibre ports via an output microlens array 115 etched directly into the optical substrate. The approach of coupling and monitoring the pump beams into the output EFD ports is similar to that described in the preceding section and
25 illustrated in Figure 4.

This optical amplifier 200 provides high output power and low noise, making it possible to cascade a multiplicity of optical amplifiers carrying high channel counts at high bit rates. In addition, high-level of electronic and optical integration for efficient automatic gain control via software, can be embedded. A digital control
30 system can be implemented, which features an easy-to-use interface and

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command set. Integration of the amplifier is achieved using a standard +5 VDC and GND power lines and a RS-232 interface.

The features and advantages of the preferred embodiment of the multi-port optical amplifier 200 described above can be summarised as follows:

- 5 - High port counts: > 64 input/output amplifier ports.
- High output power: > 70 mW of pump power can be coupled into the core of each output doped fibre, leading to more than 30 mW of signal power.
- Low noise figure: The use of appropriate pump wavelengths (980 nm) results in low noise figure (~3-6 dB).
- 10 - Potential of gain flatness: Gain flattening filters can be integrated with the doped fibres to provide flat gain across the entire band.
- Variable gain: The gains of the individual ports can independently be adjusted to support a wide range of fibre span lengths and optical network components losses. The amplifier can be configured via simple software commands – using
15 the method described above
- Signal and pump monitoring: Built-in monitoring can be provided by the bonded photodetector array 125, and the pump beam photodetector array integrated in the UTS chip 108.

20 Volume production: The amplifier of preferred embodiments of the present invention is suitable for volume production.

Throughout the specification, unless the context requires otherwise, the word “comprise” or variations such as “comprises” or “comprising”, will be understood to imply the inclusion of a stated integer or group of integers but not the exclusion of any other integer or group of integers.

25 Various modifications are possible within the scope of the present invention.

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The Claims Defining the Invention are as Follows:

1. An optical amplifier comprising:

input means for receiving input optical signals;

beam generating means for generating pump beams; and

5 waveguide means for receiving the optical signals from the input means, and pump beams from the beam generating means, the waveguide means being arranged to absorb the received pump beams and operable to amplify the received optical signal using stimulated emission of radiation, the pump beams being used to
10 drive the waveguide means to provide the stimulated emission;

wherein the beam generating means is a vertical cavity surface emitting laser.
2. An optical amplifier according to claim 1, further comprising routing means for receiving the input optical signals from the input means, and pump
15 beams from the beam generating means, and for routing the received input optical signals and the pump beams to the waveguide means.
3. An optical amplifier according to claim 2, wherein the routing means comprises a glass or sapphire substrate.
4. An optical amplifier according to claim 2 or 3, wherein the routing means
20 includes collimating and focusing means.
5. An optical amplifier according to claim 4, wherein the collimating and focusing means comprise a microlens array.
6. An optical amplifier according to claim 4, wherein the collimating and focusing means comprise diffractive optical elements.

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7. An optical amplifier according to any preceding claim, further comprising monitoring means for monitoring the power of the optical signals and the pump beams.
8. An optical amplifier according to claim 7, wherein the monitoring means is a two-dimensional photodetector array.
9. An optical amplifier according to claim 8, wherein the vertical cavity surface emitting laser is an integrated circuit, integrated with the photodetector array.
10. An optical amplifier according to any preceding claim, wherein the input means has a multi-port configuration.
11. An optical amplifier according to claim 10, wherein the input means comprises an array of optical fibres.
12. An optical amplifier according to any preceding claim, wherein the waveguide means has a multi-port configuration.
13. An optical amplifier according to claim 12, wherein the waveguide means comprises an array of optical fibres.
14. An optical amplifier according to claim 13, wherein the fibres in the array of optical fibres are either core-pumped or cladding-pumped.
15. An optical amplifier according to claim 13 or 14, wherein the array of optical fibres comprises erbium-doped alumino-silicate fibres, or praseodymium-doped fluoride fibres.
16. An optical amplifier according to any preceding claim, wherein the vertical cavity surface emitting laser operates in transverse single-mode.
17. An optical amplifier according to any one of claims 1 to 15, wherein the vertical cavity surface emitting laser operates in multi-mode.

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18. An optical amplifier according to any preceding claim, wherein the vertical cavity surface emitting laser is arranged with an external cavity resonator.
19. An optical amplifier according to any preceding claim, further comprising a first detecting means for detecting pump beam signals, and a processor to which pump beam monitoring signals are supplied, from the first detecting means, in response to the detected pump signals, the processor being operable to generate control signals for controlling the pump beam generating means, in response to the pump beam monitoring signals.
20. An optical amplifier according to claim 19, wherein the first detecting means is a photodetector array integrated on a semiconductor chip.
21. An optical amplifier according to claim 19 or 20, further comprising a second detecting means for detecting the input signal beams, with input monitoring signals being supplied from the second detecting means to the processor in response to detected input signals, the processor being operable to generate control signals for controlling the beam generating means, in response to received input monitoring signals, and pump beam monitoring signals.
22. An optical amplifier according to claim 21, wherein the second detecting means is a photodetector array.
23. An optical amplifier comprising:
- an optical substrate having top and bottom faces and two side faces extending between the top and bottom faces so that the substrate has a square-shaped cross-section;
- an input fibre array and an output doped fibre array respectively coupled to the side faces in alignment with each other, the input fibre array supplying input beams;

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a vertical cavity surface emitting laser (VCSEL) array and a top photodetector array arranged in series proximate to the top face, the VCSEL array generating pump beams;

5 a bottom photodetector arranged proximate to the bottom face in alignment with the VCSEL array and the top photodetector array;

10 a routing element arranged in the substrate at 45° to the side faces having a beam splitting lower surface and a reflective upper surface, the lower surface transmitting a major portion of the input beams to the output doped fibre array and reflecting a minor portion of the input beams to the bottom photodetector array, the upper surface reflecting the pump beams to the output doped fibre array; and

15 a processor for adjusting the power level of the pump beams in response to the power levels detected by the top and bottom photodetector arrays so that the gain of the optical amplifier can be selectively controlled.

24. An optical amplifier according to claim 23, further comprising an input microlens array etched in the optical substrate for collimating the input beams.
- 20 25. An optical amplifier according to claim 23 or 24, further comprising an output microlens array etched in the optical substrate for coupling the input beams and the pump beams to the output doped fibre array.
26. An optical amplifier according to any one of claims 23 to 25, wherein the bottom photodetector array is flip-chip bonded to the optical substrate.
- 25 27. An optical amplifier according to any one of claims 23 to 26, wherein the VCSEL array is flip-chip bonded with an Ultra-Thin Semiconductor (UTS) chip that integrates the top photodetector array.

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28. An optical amplifier according to any one of claims 23 to 27, wherein the output doped fibre array is an erbium doped fibre array.
29. An optical amplifier according to any one of claims 23 to 28, wherein the optical substrate comprises a glass or sapphire substrate.
- 5 30. A method for controlling the optical gains of an optical amplifier, the amplifier comprising at least one optical fibre amplifier and a pump source, the method comprising the steps of:
- measuring the power of pump beams generated by the pump source and deriving a first signal representative thereof;
- 10 measuring the power of input optical signals and deriving a second signal representative thereof;
- estimating the signal gain based on the measured input signal power and pump power, and deriving a third signal representative of the difference between the measured signal gain and the desired
- 15 signal gain;
- processing the first, second, and third signals to generate a pump source driving current profile in response to the processed first, second and third signals; and
- controlling the generation of driving current profile to achieve the
- 20 desired output power for the pump beam.
31. An optical amplifier substantially as hereinbefore described with reference to the accompanying drawings.
32. A method for controlling the optical gains of an optical amplifier substantially as hereinbefore described with reference to the
- 25 accompanying drawings.

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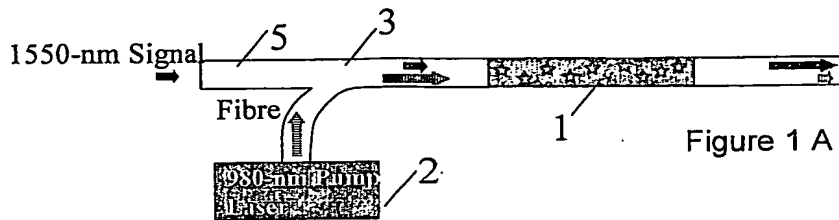


Figure 1 A

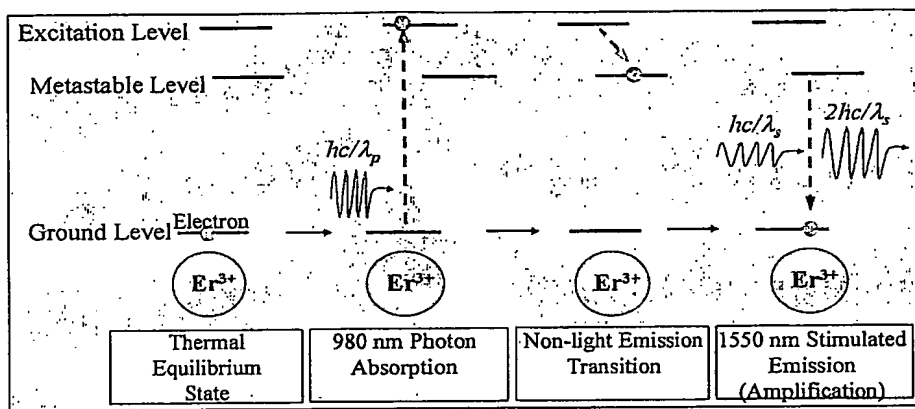


Figure 1 B

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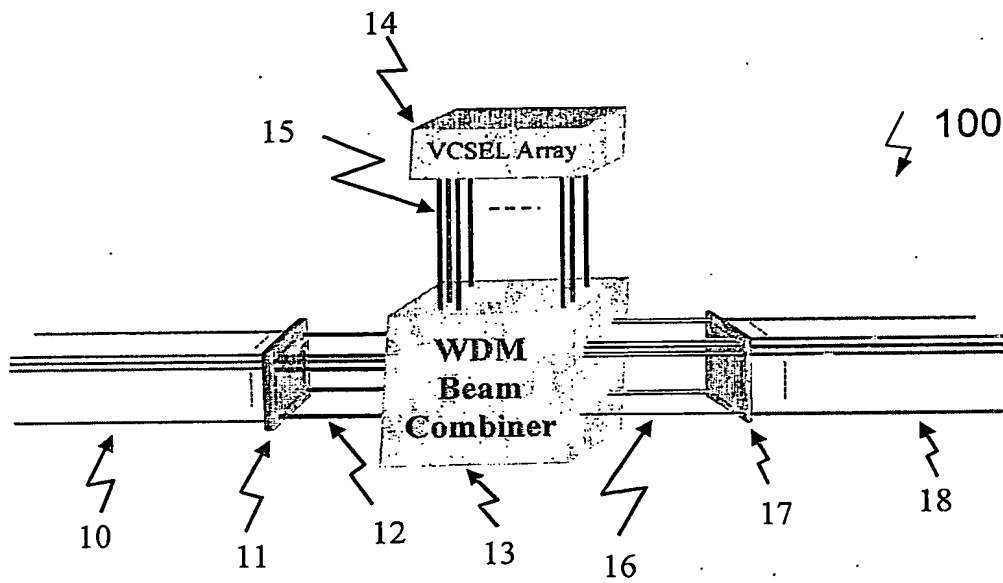


Figure 2

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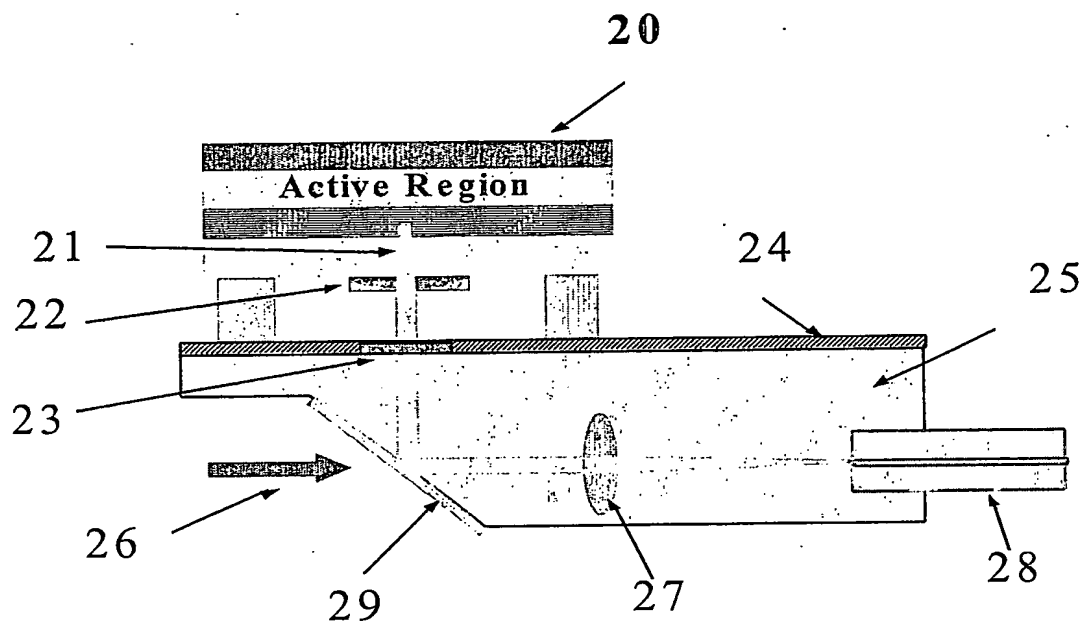


Figure 3

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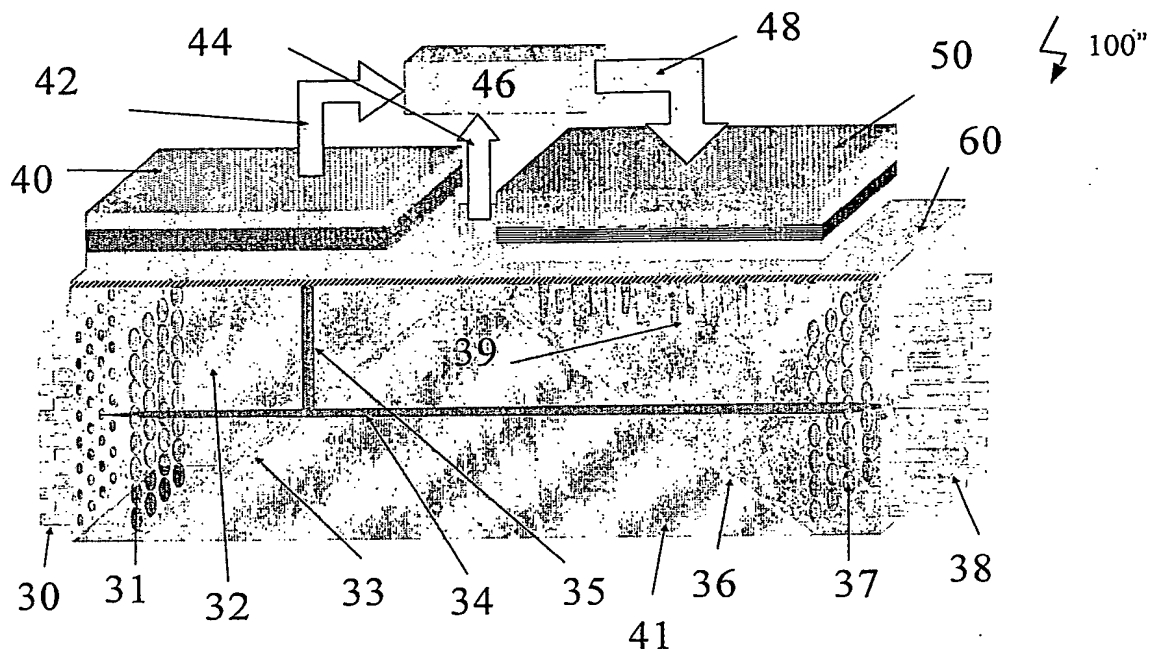


Figure 4

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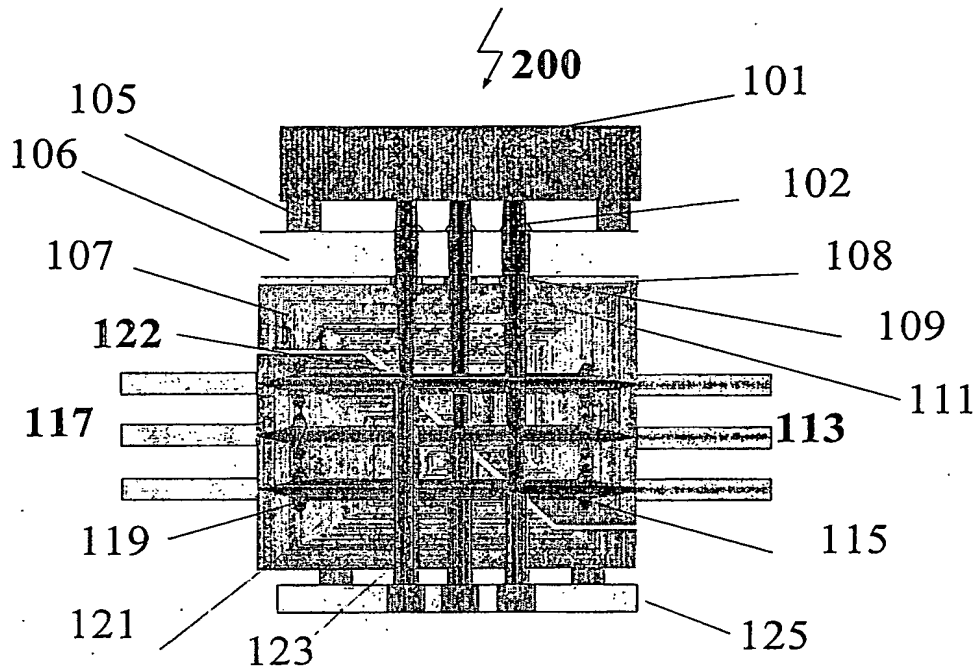


Figure 5

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2003/001439

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl. ⁷: H04B 10/17, H01S 3/102

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

DWPI, JAPIO Keywords: (i) vcsel, vertical cavit; amplif; pump
(ii) optic; amplif; H04B 10/17; pump, signal; power, intensit, gain; adjust, control, feedback, chang

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P, X	US 2003/0112498 A (Nikonov et al.) 19 June 2003 Paragraphs 17-23, Figure 3	1-4, 6, 12-14
X	WO 2001/067563 A (NOVALUX, INC.) 13 September 2001 Pages 3, 19-20, claims 29-31	1-2, 4, 6-7, 10-18
Y		19, 21
X	US 5301201 A (DUTTA et al.) 5 April 1994 Columns 2-4, Figure 4	1-2, 4-7, 10- 17
Y		19, 21

☒ Further documents are listed in the continuation of Box C

☒ See patent family annex

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier application or patent but published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
16 January 2004

Date of mailing of the international search report
22 JAN 2004

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INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2003/001439

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2002/0027706 A (PARK et al.) 7 March 2002 Page 2, Figure 1	30 19, 21
Y A	US 6407854 B (SHUM) 18 June 2002 Column 5 line 67 - column 6 line 8	19, 21 30, 32
NOTE: for the Y indications, either of WO 2001/067563 and US 5301201 may be combined with either of US 2002/0027706 and US 6407854.		

INTERNATIONAL SEARCH REPORT

International application No.

PCT/AU2003/001439

Box I Observations where certain claims were found unsearchable (Continuation of Item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos :
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos :
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☐ Claims Nos :
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)

Box II Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. Claims 1-29, 31
2. Claims 30, 32

as reasoned on the extra sheet.

1. ☒ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims
2. ☐ As all searchable claims could be searched without effort justifying an additional fee, this Authority did not invite payment of any additional fee.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest.
- ☒ No protest accompanied the payment of additional search fees.

Supplemental Box

(To be used when the space in any of Boxes I to VIII is not sufficient)

Continuation of Box No: II

The international application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept. In coming to this conclusion the International Searching Authority has found that there are different inventions as follows:

1. Claims 1-29, 31 are directed to an optical amplifier wherein pump beams are generated by a vertical cavity surface emitting laser. It is considered that the *use of a vertical cavity surface emitting laser to generate the pump beams* comprises a first "special technical feature".
2. Claims 30, 32 are directed to a method of controlling optical amplifier gain, by processing signals related to measured signal and pump powers to generate a corresponding pump source driving profile. It is considered that *processing signals related to measured signal and pump powers, to generate a corresponding pump source driving profile*, comprises a second "special technical feature".

The feature common to all of the claims is an optical amplifier having a pump source, with amplification of signals via stimulated emission induced by pump beams. However this common feature is generic in the art of fibre amplifiers. Consequently the common feature does not constitute "a special technical feature" within the meaning of PCT Rule 13.2, second sentence, since it makes no contribution over the prior art. Since there exists no other common feature which can be considered as a special technical feature within the meaning of PCT Rule 13.2, second sentence, no technical relationship within the meaning of PCT Rule 13 between the different inventions can be seen. Consequently it appears that a posteriori, the claims do not satisfy the requirement of unity of invention.

Furthermore, the groups of claims include distinct classifications under the IPC (eg, H01S 5/183 in relation to the first group of claims, and H01S 3/102 in relation to the second group of claims) and therefore constitute separate search areas, and hence these inventions could not be searched without involving significant extra effort.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/AU2003/001439

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member			
US	2003112498	WO	03052887		
WO	0167563	AU	60997/01	EP	1264374
US	5301201	EP	0614256	JP	6318765
US	2002027706	EP	1187275	JP	2002118316
				KR	2002019688
US	6407854	AU	41646/01	EP	1264372
				WO	0167141
END OF ANNEX					